

An Experimental Study on the Effect of Sequential Transverse and Lateral Markings on Perceived Speed on a Single-lane Straight Road

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Abstract

We focus on the vehicle speed inducement effect of sequence patterns of transverse and lateral markings on a single-lane straight road. We test the effectiveness of several sequence patterns through experiments with a driving simulator. The sequence patterns are characterized by patterns of progressively and concurrently reduced spacing of transverse lines on the road surface and lateral poles on the roadside. We examine the discrepancy between vehicle speed and speed perceived by the drivers under the influence of several sequence patterns, estimating driver-perceived speed using a hidden Markov model. Experiments show that (1) perceived speed tends to be higher than actual vehicle speed, except for patterns where lines and poles were equally spaced in all intervals or where spacing was greatly decreased in the middle intervals, and (2) in the case of a pattern where spacing was greatly decreased in the first intervals, vehicle speed rapidly decreased while the perceived speed remained high.

Keywords: Road markings; Speed inducement; Sequence effect; Perceived speed; Discrepancy between objectivity and subjectivity; Hidden Markov model; Driving simulation experiment

Introduction

Traffic administrators in Japan are devising a variety of road marking patterns designed to reduce vehicle speeds for improved traffic safety. One such pattern consists of transverse lines with progressively reduced spacing to give drivers the impression that their speed is increasing. The road markings verified as inducing a deceleration effect on multi-lane straight roads include “optical dot” road-surface markings at the Bijogi Junction Saitama-Omiya Line of the Metropolitan Expressway Company [1] and “sequence design” tunnel wall markings in the Inariyama tunnel on the Hanshin Expressway Company’s Kyoto Line [2]. However, we do not well understand how the patterns of progressively reduced spacing in these cases actually induce drivers to decelerate.

We focus on the mechanism by which patterns of sequential transverse and lateral markings induce drivers to decelerate, and test the effectiveness of various markings on a single-lane straight road through in-house experiments with a driving simulator. We define a “sequence pattern” as the alignment of progressively and concurrently reduced spacing of transverse lines on the road surface and lateral poles on the road side, “transverse and lateral markings” as road markings with a sequence patterns, and a “sequence effect” as a vehicle speed inducement effect produced by sequence patterns.

Denton [3-5] provides pioneering research regarding speed inducement mechanisms of road markings with sequence patterns. Conducting an in-house experiment with a driving simulator called a “dynamic visual field generator,” Denton tested the hypothesis that when driving a vehicle over road markings with a pattern of progressively reduced spacing after having adapted to a constant speed on a single-lane straight road, drivers decelerate due to an illusion of acceleration. His research was continued by a number of successors, whose findings included the following: (1) Road markings with sequence patterns may lessen the distribution variance of the platoon speed of several vehicles [6]. (2) Sequence effects may differ over the short and long term [7]. (3) Peak periods of vehicle deceleration may shift with different sequence

patterns [8]. (4) The trigger point to remind drivers to slow down may vary with road section length [9]. (5) Shapes such as chevrons, herringbone, and transverse bars may influence sequence effects [10-14]. (6) Tunnel wall markings, sound insulation wall markings, and other lateral markings may have different sequence effects from those of road surface markings [15,16].

Regarding speed reduction markings with progressively reduced spacing to give drivers the impression that their speed is increasing, MUTCD [17] indicates that the sequence pattern itself assumes a key role in the vehicle speed inducement effect. However, we do not necessarily understand the mechanism behind how sequence patterns induce deceleration.

We focus on driver speed perceptions to study mechanisms of the vehicle speed inducement effect, under the assumption of their involvement in discrepancies between perceived and actual speed. In a driving scene where transverse and lateral markings are displayed on the road, optic flows [18] generally cause the driver to perceive movement of objects in the scene at a speed relative to the vehicle speed. We hereby define “perceived speed” as this relative speed perceived by the driver.

This study empirically analyzes discrepancies between actual and perceived speed under the influence of transverse and lateral sequence patterns on a single-lane straight road simulated in in-house experiments, while estimating perceived speed using a hidden Markov model (HMM).

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Methods

Procedure

We first conduct a driving simulation experiment with a driving simulator (DS) under several types of sequence patterns. In this experiment, vehicle speed transitions are investigated in relation to the sequence patterns.

We then conduct a “perception experiment” to investigate relationships in the change rate between vehicle and perceived speed for a given sequence pattern. In this experiment we prepare two types of recorded moving pictures (MP). The first is a reference MP in which sequence patterns are displayed at a constant speed on the DS screens display. The second is a comparison MP in which the sequence pattern type and MP playback speed differ from the reference MP.

Finally, we use an analytical model to estimate the perceived speed for a given sequence pattern from changes in the vehicle speed. The perception experiment easily analyzes correspondence relationships, but not transitioning. In contrast, the DS experiment easily measures vehicle speed, but not continuous data related to perceived speed. For these reasons, we estimate transitions of perceived speed using a HMM. In this study, the change rate of perceived speed is a discrete latent variable of the HMM and the transition of change rate of vehicle speed observed under each sequence pattern is supervised data of the HMM.

Modeling the markings

We can divide a single-lane straight road with transverse and lateral markings into D sections. Let \mathbf{D} be the set of all sections. Transverse lines and lateral poles are located at equally-spaced intervals in each section $d \in \mathbf{D} = \{1, \dots, D\}$. The degree of the equally spaced intervals in an arbitrary section $d+1 \in \mathbf{D}$ decreases at a rate greater than that in the previous section d . Hence, comparing two adjacent sections, the degree of spacing in each section decreases in the direction of vehicle forward movement in \mathbf{D} , although there is equal spacing within the limits of each section. This study treats alignment like this as the sequence pattern.

Preparing Q patterns as the sequence pattern, we let \mathbf{Q} be a set of all patterns. We define l_d^q as the interval between markings in d , locating lines and poles with an arbitrary sequence pattern $q \in \mathbf{Q} = \{1, \dots, Q\}$. Then we use l_d^q to prepare an indicator defined as $\Delta_d^q = (l_d^q - l_{d-1}^q) / l_{d-1}^q$. We refer to this indicator Δ_d^q as the “decrease rate” of l_d^q .

Setting the class

When N drivers respectively drive M times in \mathbf{D} , we let \mathbf{N} and \mathbf{M} are the set of all drivers and the set of drive frequencies for each driver, respectively. When driver $n \in \mathbf{N}$ drives m times as the $m \in \mathbf{M}$ in section d with pattern q , we let v_o^{dqnm} be the average vehicle speed for drive m . In the DS experiment, v_o^{dqnm} is calculated by averaging the series of instantaneous vehicle speeds measured every 0.02 sec within d . We use v_o^{dqnm} to define $\Delta_o^{dqnm} = (v_o^{dqnm} - v_o^{d-1,qnm}) / v_o^{d-1,qnm}$ as the “change rate” of the vehicle speed v_o^{dqnm} . For the sake of expedience, we define the “perceived speed” v_s^{dqnm} responding according to v_o^{dqnm} . We also define Δ_s^{dq} as a change rate of v_s^{dq} that is representative of all drivers in section d with pattern q .

The problem is that v_s^{dqnm} is difficult to directly measure in the DS experiment. Therefore, transitions of Δ_s^{dq} are estimated by an HMM

based on observed data for transitions of Δ_o^{dqnm} . A HMM is a Markov chain of each discrete latent variable in combination with some discrete observed variables. However, Δ_s^{dq} and Δ_o^{dqnm} are not discrete, but rather continuous positive and negative rates. We thus propose discretizing to partitions by “class,” as we explain below in detail, to each Δ_s^{dq} and Δ_o^{dqnm} . Accordingly, the class of Δ_s^{dq} is a discrete latent variable, while the class of Δ_o^{dqnm} is a discrete observed variable in the HMM.

The term “class” means a partition of the change rate of speed over a common range regardless of section, sequence pattern, driver, or drive frequency. We first explain how to partition Δ_o^{dqnm} into several classes: Δ_o^{dqnm} is divided into K parts, each with upper limit $\bar{\tau}_k$ and lower limit $\underline{\tau}_k$ (where $k \in \{1, \dots, K\}$ and $\bar{\tau}_k = \underline{\tau}_{k+1}$), regardless of d, q, n, m . When Δ_o^{dqnm} belongs to the k th class, we let this class be C_{ok}^{dqnm} , defined as $C_{ok}^{dqnm} = \{\underline{\tau} \leq \Delta_o^{dqnm} \leq \bar{\tau}_k\}$. To partition Δ_s^{dq} into classes, the number of the class of Δ_s^{dq} is K , as for C_{ok}^{dqnm} . When Δ_s^{dq} belongs to the k th class, we let the class be C_{sk}^{dq} . The upper limit $\bar{\tau}_k$ and lower limit $\underline{\tau}_k$ of C_{sk}^{dq} are the same as that of C_{ok}^{dqnm} .

Transition of the perceived speed

We next explain how to estimate transitions of the perceived speed v_s^{dq} through all sections \mathbf{D} for a sequence pattern q : Using the HMM we can estimate a course that the optimal C_{sk}^{dq} can steer through, to maximize occurrence probability of each C_{sk}^{dq} in \mathbf{D} . When the optimum course has been estimated, transitions of the upper and lower limits of the change rate Δ_s^{dq} can be estimated. Accordingly, a transition of v_s^{dq} can be estimated for a given sequence pattern q given an initial value of v_s^{dq} . Based on this estimation, discrepancy in the transition between v_s^{dq} and v_o^{dq} can be analyzed, where $v_o^{dq} = \sum_{n=1}^N \sum_{m=1}^M v_o^{dqnm} / (NM)$.

We assume the Markov property for transitions of C_{sk}^{dq} . Using conditional probability, this property can be expressed as $\Pr(C_S^{dq} | C_S^{d-1,q}, C_O^{d-1,q}, \dots, C_S^{1,q}, C_O^{1,q}) = \Pr(C_S^{dq} | C_S^{d-1,q})$. We let p_{lk}^d be the transition probability from $C_{Sl}^{d-1,q}$ to C_{Sk}^{dq} . Assuming that p_{lk}^d does not depend on d , we let p_{lk} be a homogeneous transition probability. Now, suppose C_{Oh}^{dq} is obtained in $d-1$. When we let $\Pr(C_{Sk}^{dq})$ be an occurrence probability of C_{Sk}^{dq} , the optimal $\Pr(C_{Sk}^{dq})$ is calculated by $\max \Pr(C_{Sl}^{d-1,q}) p_{lk} \Pr(C_{Sl}^{d-1,q} | C_{Oh}^{d-1,q})$ by the Viterbi algorithm [19] and p_{lk} is calculated via the Baum–Welch algorithm [20]. Regarding estimation of $\Pr(C_{Sl}^{d-1,q} | C_{Oh}^{d-1,q})$, we utilize the results of the perception experiment, as explained later in detail. We executed the above calculations using R [21].

Experimental design

DS Experiment: The roadway displayed on the DS screen represents a two-lane bi-directional intercity expressway typical of Japan. Total width of the roadway is 13 m, comprising two 3.5 m lanes, a 1.5 m median strip, two 1.75 m left shoulders, and two 0.5 m right shoulders. In the transverse and lateral markings illustrated in Figure 1, the width of each transverse line in the direction of vehicle movement is 45 cm, and the length perpendicular to the lane is 3.5 m. The height of each lateral pole is 2.5 m.

Table 1 shows the eight sequence patterns presented to the test subjects. The five sections labeled I–V in Table 1 were preceded by a 600 m run-up section in which the drivers accelerated from speed zero. The length of each section I–V was 100 m, in consideration of habituation effects while driving on the markings. The last 100 m in the

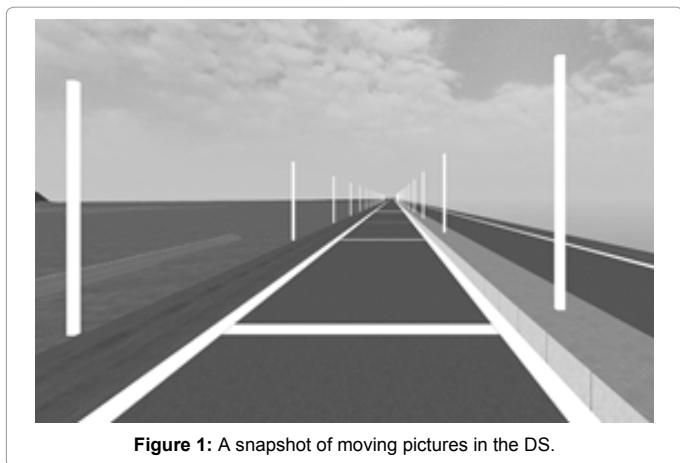


Figure 1: A snapshot of moving pictures in the DS.

run-up section is labeled as section Z in Table 1. We refer to the average speed in section Z as an “initial value” of the speed.

Each of the eight sequence patterns shown in Table 1 has the following characteristics: Types 1, 2, and 3 have the same respective decrease rates Δ_d^1 , Δ_d^2 , and Δ_d^3 through all sections I–V. Types 4, 5, and 6 have respectively greater decrease rates Δ_d^4 , Δ_d^5 , and Δ_d^6 in the beginning, middle, and end sections than in the remaining sections. Type 7 has a zero decrease rate because of its equally spaced intervals. Type 8 has a different initial interval value in Z from the other types, although its sequence pattern is the same as that of type 2. Concerning decrease rates from I to V, any of 5%, 10%, or 15% has been applied to the rates, except type 7.

The test subjects were five fourth year students at Kobe University, each of whom had a driver’s license. Figure 2 shows a scene from the experiment. No speedometer is displayed on the DS screen during the experiment, although Figure 2 shows one for convenience. The tests were run three times for each sequence pattern. The experimenter instructed each subject to maintain a constant speed while looking into the far distance along the road in the DS screen.

Perception experiment: The experimenter prepared a baseline MP displaying markings at 12 m intervals and displayed at a fixed speed of

70 km/h. The baseline MP was created from a transcription of a driver running at a fixed speed in the type 7 sequence pattern. The experimenter also prepared comparison MPs for contrast with the baseline MP. The experimenter told test subjects the interval and playback speed values of the baseline MP, but not those of the comparison MPs.

We prepared 32 comparison MPs, shown in Table 2. The experimenter showed each subject the baseline MP for 3 s, then each of the 32 cases for 3 s in random order. Subjects immediately chose upper and lower playback speed limits for the comparison MP to estimate speeds in 2 km/h increments in the range 44–100 km/h. This process was repeated nine times, and we took the median value of the upper and lower limits chosen by the subject as the perceived speed of the subject.

Analysis Results

Results of the experiments

Figure 3 shows vehicle speed data obtained in the DS experiment. Since the DS measured instantaneous vehicle speed every 0.02 s, we averaged all spot speeds per number of data within each section. We refer to this as the “average spot speed.” Each subject ran each sequence pattern three times in the DS experiment. We hereinafter refer to an average of the three average spot speeds as a “section speed” of the vehicle. Because each subject tried to drive at a constant speed but without reference to a speedometer, the section speeds are distributed as shown in Figure 3.

In Figure 3, in sequence patterns 3, 4, 5 and 6 in which the decrease rate of line and pole spacing was 15% in all intervals, in the first intervals, in the middle intervals and in the last intervals, respectively, each standard deviation of section speed of five subjects has a large value in the section in which the decrease rate was set at 15%. In sequence pattern 7 in which spacing was equal 12m in all intervals, each transition of section speed of five subjects stays relatively steady and each standard deviation of section speed has a small value in all sections.

Figure 4 shows the relationship between subject- perceived speeds and the playback speed of comparison MPs, that is, vehicle speed. Figure 4 displays nine dots for each of the four decrease rates because each subject performed each test nine times. Each dot indicates the average

Table 1: The eight sequence patterns.

	Section	Z	I	II	III	IV	V
1	Interval [m]	12.00	11.40	10.83	10.29	9.77	9.29
	DR [%]	0	5	5	5	5	5
2	Interval [m]	12.00	10.80	9.72	8.75	7.87	7.09
	DR [%]	0	10	10	10	10	10
3	Interval [m]	12.00	10.20	8.67	7.37	6.26	5.32
	DR [%]	0	15	15	15	15	15
4	Interval [m]	12.00	10.20	9.18	8.72	8.28	7.87
	DR [%]	0	15	10	5	5	5
5	Interval [m]	12.00	11.40	10.26	8.72	7.85	7.46
	DR [%]	0	5	10	15	10	5
6	Interval [m]	12.00	11.40	10.83	10.29	9.26	7.87
	DR [%]	0	5	5	5	10	15
7	Interval [m]	12.00	12.00	12.00	12.00	12.00	12.00
	DR [%]	0	0	0	0	0	0
8	Interval [m]	7.00	6.30	5.67	5.10	4.59	4.13
	DR [%]	0	10	10	10	10	10

Interval: the interval between markings l_d^q . DR: the decrease rate $\Delta_d^q = (l_d^q - l_{d-1}^q) / l_{d-1}^q$.



Figure 2: A scene of the DS experiment.

Table 2: 32 moving picture comparisons.

Case	1	2	3	4	5	6	7	8
DR [%]	0	0	0	0	0	0	0	0
Speed [km/h]	55	60	65	67	69	70	72	75
Case	9	10	11	12	13	14	15	16
DR [%]	5	5	5	5	5	5	5	5
Speed [km/h]	55	60	65	67	69	70	72	75
Case	17	18	19	20	21	22	23	24
DR [%]	10	10	10	10	10	10	10	10
Speed [km/h]	55	60	65	67	69	70	72	75
Case	25	26	27	28	29	30	31	32
DR [%]	15	15	15	15	15	15	15	15
Speed [km/h]	55	60	65	67	69	70	72	75

DR: the decrease rate $\Delta_d^q = (I_d^q - I_{d-1}^q) / I_{d-1}^q$ Speed: the comparison speed as contrasted with the baseline.

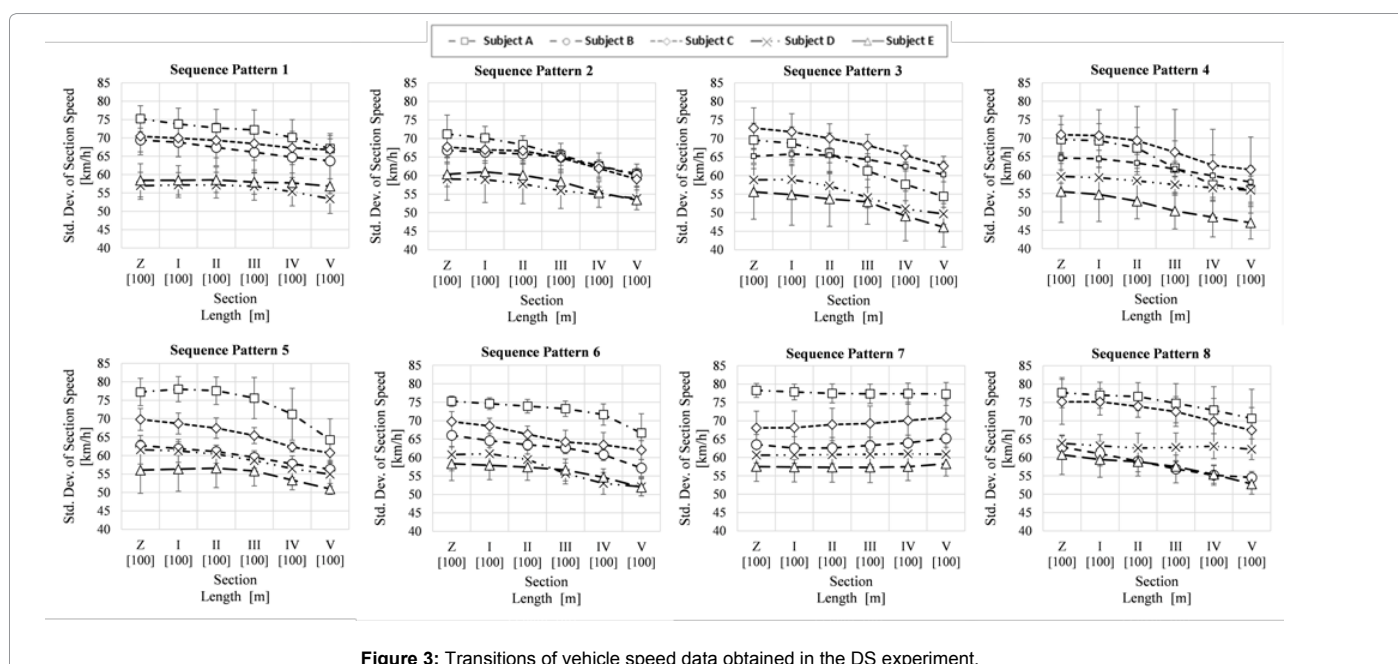
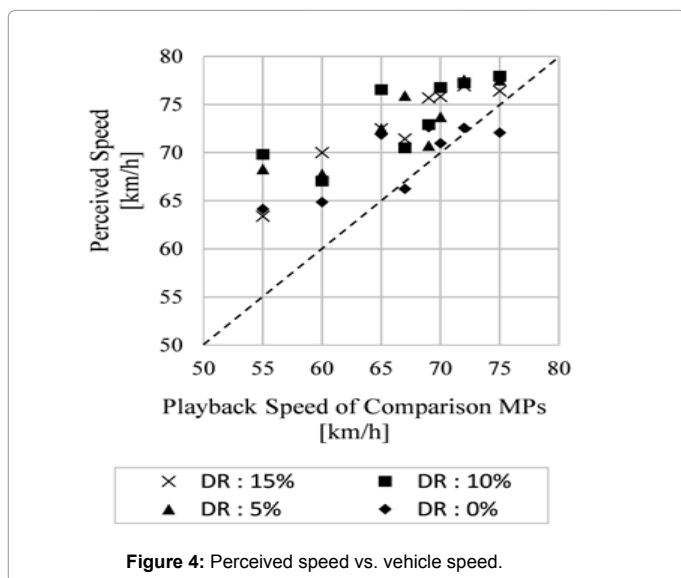


Figure 3: Transitions of vehicle speed data obtained in the DS experiment.

value of five subjects in the eight cases belonging to the same decrease rate in Table 2. Figure 4 shows that the subjects had a propensity to overestimate vehicle speed, regardless of the marking decrease rate.

Results of the estimation

Considering the results of a goodness-of-fit test on the data obtained from the DS experiment (Table 4), we used the seven classes shown in Table 3. Values for the change rate of vehicle speed Δ_o^{dqnm} were statistically identical among the decrease rates Δ_d^q , represented as 5%, 10%, and 15% in Table 4, so we set the upper and lower limits of each class as shown in Table 3. The *, **, and *** symbols in Table 4 indicate that the null hypothesis is rejected at 10%, 5%, and 1% levels of significance for a two-sided test, respectively. For instance, in the case of class 2, where the P value of a chi-square test was 0.053, the null hypothesis “the value of Δ_d^q is statistically independent for each Δ_d^q in the class” was regrettably rejected at the 5% level of significance. In general, however, the null hypotheses are not rejected for most classes at least at a 1% level of significance.



Since we have seven classes, the data series of C_{Ok}^{dqnm} can be obtained from the results of the DS experiment. We applied the Baum–Welch algorithm to the data series to estimate p_{lk} . Using the $\Pr(C_{Sl}^{d-1,q} | C_{Oh}^{d-1,q})$ estimated from the results of the perception experiment, we can calculate $\Pr(C_{Sk}^{dq}) = \max \Pr(C_{Sl}^{d-1,q}) p_{lk} \Pr(C_{Sl}^{d-1,q} | C_{Oh}^{d-1,q})$ using the Viterbi algorithm. From the upper limits of C_{Sk}^{dq} and the initial value of v_s^{dq} , the transition of v_s^{dq} can be estimated for each sequence pattern.

From the above, as shown in Figure 5 we found the characteristics of discrepancy between actual and perceived speed for each sequence pattern.

Discussion

Figure 5 shows the perceived speed for a given sequence pattern and vehicle speed. As that figure shows, the following characteristics were found in the relationship between perceived and actual vehicle speed.

Except for sequence patterns 1 and 5, perceived speeds were significantly higher than actual vehicle speeds. Perceived speeds for sequence patterns 1 and 5, in contrast, were estimated to decrease gradually with vehicle speed. In sequence pattern 7, which has equally spaced intervals, perceived speed was estimated to gradually increase above the vehicle speed, despite the vehicle speed being constant. In sequence patterns 2 and 8, which both had the same Δ_d^q in sections I–V and different initial l_d^q in section Z, the difference in the initial interval influenced the perceived speed.

Conclusion

Our experiments resulted in five main findings:

- In a sequence pattern in which decrease rate of line and pole spacing was equal 5% in all intervals and one where decrease rate of spacing was greatly increased in the middle intervals, the perceived vehicle speed tended to descend.
- In most sequence patterns other than those above, the perceived vehicle speed was higher than the actual speed.

Table 3: Class settings.

Class	1	2	3	4	5	6	7
UL(%)	-100	-8	-4	-2	-1	0	3
LL(%)	-8	-4	-2	-1	0	3	100

UL: the upper limit τ_k in class τ_k . LL: the lower limit τ_k .

Table 4: Goodness-of-fit test for classes.

Class	Number of Δ_o^{dqnm} for each of the three Δ_d^q			P value of χ^2 test	
	5%	10%	15%		
1	4	10	7	0.276	
2	32	49	30	0.053	*
3	50	57	34	0.052	*
4	44	55	29	0.018	**
5	53	43	27	0.015	**
6	33	26	16	0.054	*
7	18	12	1	0.001	***
Total	234	252	144		

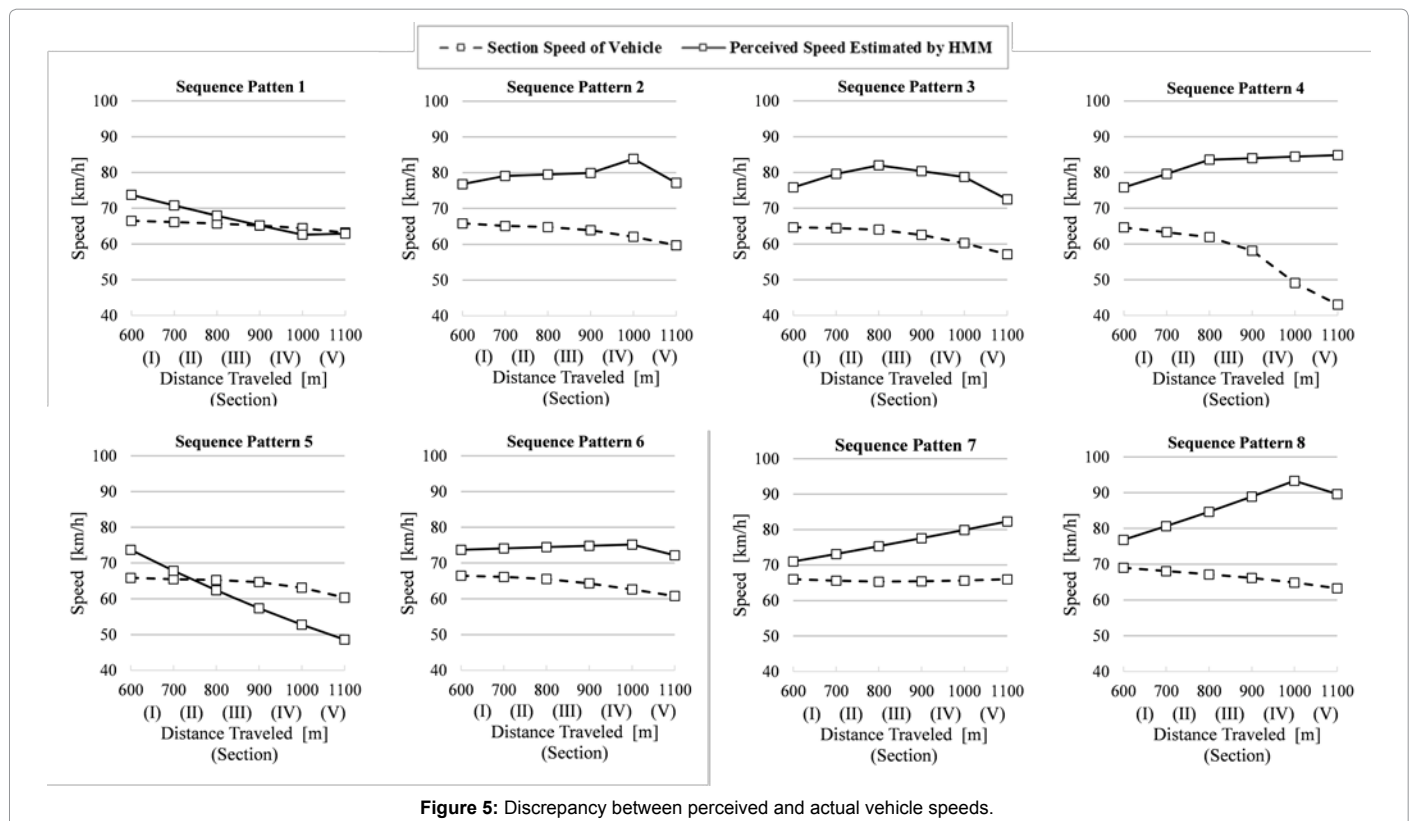


Figure 5: Discrepancy between perceived and actual vehicle speeds.

- In two sequence patterns in which decrease rates of spacing were respectively 10% and 15% in all intervals, trend of the perceived vehicle speeds was different from that in a pattern where decrease rate of spacing was equal 5%.
- In a sequence pattern in which decrease rate of spacing was greatly increased in the first intervals, vehicle speed rapidly decreased while the perceived speed remained high.
- In a sequence pattern in which spacing was equal 12m in all intervals, vehicle speed did not nearly change while the perceived speed was greatly increased.

Several outstanding issues remain. We need to examine vehicle speed behavior at a given perceived speed, the opposite case of the situation examined in this study. We also need to empirically analyze differences in sequence pattern effects that give drivers the impression that their speed is increasing, and the feeling of speed that the DS itself invokes. Finally, we need to study the impact of rapid deceleration of a lead vehicle on following vehicles after the lead vehicle encounters transverse and lateral markings, and whether a resulting accident is a concern.

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